Far Infrared Loud Quasars 1: Disturbed and Quiescent Quasars in the PG Survey

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ABSTRACT

We use host galaxy imaging studies of the PG Quasar survey to compare the far-infrared (FIR) properties of quasars with disturbed and undisturbed host galaxies. By using survival analysis, we show that the quasars with disturbed host galaxies, with morphologies classified from a homogenous data set, have a $60\mu m$ luminosity distribution that is different from that of those with undisturbed hosts with >97% confidence. For morphological classifications using an inhomogenous data set, including HST data for some objects, this confidence rises to >99% confidence. The mean $60\mu m$ luminosity of the disturbed–host quasars is several times greater than that of the undisturbed-host quasars. However, possible biases in the PG survey might affect these conclusions. Our results are interpreted as supporting the idea that quasars are related to at least some Ultraluminous Infrared Galaxies. We discuss the implications of this result for studies of quasar and galaxy evolution.

Key words: infrared;quasars – quasars;infrared – galaxies;interacting – quasars;hosts

1 INTRODUCTION

The host galaxies of quasars have been the subject of intense observational scrutiny in recent years. A general picture had emerged that radio-loud quasars lie in giant ellipticals, whilst radio-quiet quasars are in spirals (e.g. Hutchings et al. (1989)). Recent results, however, have confused this picture, with some radio-quiet quasars showing signs of interacting or elliptical hosts. The most recent HST data (McLure et al. 1998) goes further to suggest that essentially all bright quasars ($M_R < -24$), whether radio loud or radio quiet, lie in elliptical galaxies. Meanwhile, there is mounting evidence that interactions and mergers between galaxies are involved in triggering QSO-like activity (eg. Stockton (1990), Hutchings & Neff (1992)). There are also a number of suggestions that some Ultraluminous Infrared Galaxies (ULIRGs) are an early stage in the evolution of quasars (Sanders & Mirabel (1996) and references therein), though much of the luminosity in the ULIRG-phase appears to be starburst rather than AGN powered (Genzel et al. 1998). ULIRG activity is strongly linked to galaxy interactions and mergers (Leech et al. 1994). Clements et al. (1996a), for example, showed that 90% of a sample of 60 ULIRGs are in disturbed systems, a result confirmed by Murphy et al. (1996) for a similar but complimentary ULIRG sample.

These results lead to a possible scenario for quasar triggering in which a galaxy merger causes gas to collapse into the nucleus of a galaxy (eg. Mirabel (1993)), initiating a starburst and fuelling an AGN. The resulting emission is obscured by dust leading to a ULIRG-like phase. The central engine then expels or destroys the obscuring material until it can be observed directly, as is the case with broad line ULIRGs (eg. Mrk231 and Mrk1014). The merging galaxies eventually settle into a stable morphology, and signs of the starburst will fade. The details of this scheme depend on the relative lifetimes of the ULIRG and quasar stages. In this scenario quasars in disturbed or interacting hosts should be at an earlier stage in their evolution from ULIRG-like object to conventional quasar. The defining characteristic of a ULIRG is extreme FIR luminosity, $L_{FIR} > 10^{12} L_{\odot}$. Therefore, the ULIRG-to-quasar evolutionary scenario predicts that quasars in disturbed host galaxies are more likely to have high FIR luminosities than quasars in undisturbed hosts.

ISO observations, of known quasars (eg. Wilkes et al. (1997)), and large area surveys which discover new FIR-bright quasars (eg. Oliver et al. (1997)), will provide significant new insights into these issues. Before these measurements are completed, though, it is timely to re-examine the properties of FIR-bright quasars as determined by the IRAS satellite and ground-based observations. Elsewhere (Clements et al., in preparation) we will discuss the results of imaging observations of a sample of quasars selected for high FIR luminosity. Here we take the alternative approach

Object	Redshift	F_{60}	F_{100}	L_{FIR}
0026+129	0.142	<27	<80	<8.1
0052+251	0.155	93	<338	<37
0157+001	0.164	2377	2322	610
0923+201	0.190	<300	<1000	<170
0947+396	0.206	201	462	110
0953+414	0.239	<129	<315	<100
1012+008	0.185	<140	<347	<66
1048+342	0.167	<140	<347	<53
1121+422	0.224	<140	<315	<94
1151+117	0.176	<154	<347	<62
1202+281	0.165	110	420	52
1307+085	0.155	<154	<347	<48
1309+355	0.184	<140	<347	<65
1322+659	0.168	<89	<257	<37
1352+183	0.158	<140	<347	<47
1354+213	0.300	<154	<347	<190
1402+261	0.164	229	340	67
1427+480	0.221	<112	<252	<73
1444+407	0.267	117	170	94
1613+658	0.129	635	1090	120
1700+518	0.292	480	482	420
0050+124	0.061	2293	2959	85
0804+761	0.100	191	<315	<21
0838+770	0.131	174	426	40
0844+349	0.064	163	294	7.5
1001+054	0.161	27	<69	<9.7
1114+445	0.144	191	<347	<47
1115+407	0.154	<140	<347	<45
1211+143	0.085	305	689	28
1229+204	0.064	163	<462	<9.3
1351+640	0.087	757	1184	62
1404+226	0.098	<154	<347	<19
1411+442	0.089	162	<175	<12
1415+451	0.114	112	260	19
1416-129	0.129	<140	<315	<30
1426+015	0.086	318	<315	<22
1435-067	0.129	<126	<315	<28
1440+356	0.077	652	1061	42
1519+226	0.137	<112	<252	<27
1552+085	0.119	<126	<315	<24
1612+261	0.131	<54	<161	<14
1617+175	0.114	<98	<252	<17
1626+554	0.133	<70	<238	<20
2130+099	0.061	479	<1000	<21
2214+139	0.067	337	<282	<13

Table 1. Properties of PG Quasars used for this study.

F_{60} and F_{100} are the 60 and 100 μm fluxes in mJy, respectively, L_{FIR} is the FIR luminosity in units of $10^{10} L_{\odot}$.

and compare the FIR properties of quasars in disturbed and undisturbed hosts to see if there is indeed a connection between disturbed host morphology and high FIR luminosity.

The rest of the paper is organised as follows. In the next section we describe the quasar sample and imaging data used for this study and arrive at morphological classifications for the host galaxies. In Section 3 we discuss the statistical methods used to compare the FIR properties of the disturbed and undisturbed quasars and find a significant difference between the two classes. These results are discussed in Section 4 and we summarise our conclusions in Section 5.

2 QUASAR HOST IMAGING SAMPLES

To assess any difference in the properties of quasars in disturbed and undisturbed hosts, we need a complete sample of objectively selected quasars for which host galaxy imaging is available. Furthermore, since we are interested in the FIR properties of these objects, we also need a sample where complete FIR observations are available.

There are very few quasar samples for which complete host-imaging data is available. Most quasar host studies to date have concentrated on small samples of quasars with a range of properties (eg. Bahcall et al. (1996), Boyce et al. (1998), McLure et al. (1998)), or have been selected from some particularly special sub-class of quasar (eg. Boyce et al. (1997)). The only survey which fits our requirement for a quasar sample with complete imaging observations is the low redshift (z<0.3) PG quasar survey (see Table 1). Extensive imaging data for these objects is available, including H-band observations by McLeod & Rieke (1994a,b) for all the objects, HST observations for many of the high luminosity objects ((Bahcall et al. 1997), (McLure et al. 1998)), and extensive ground-based imaging studies at both optical and infrared wavelengths (see Table 2 and 3). These cover a well defined subsample of the PG quasar survey (Schmidt & Green 1983), including all objects with redshift z< 0.3 and B band absolute magnitude M_B <-22.

We take FIR data on these objects from Sanders et al. (1989), which details IRAS observations in both survey and pointed mode for the complete PG sample. One of the objects in the parent sample, 1116+215, for which IRAS data are not available, is removed from further consideration. We also remove all four radio-loud quasars in the McLeod sample. Only one of these, 3c273, was detected by IRAS, and this emission is strongly dominated by non-thermal effects. Any non-thermal contribution to the FIR emission of the radio quiet quasars in the final sample is below the 10mJy level.

FIR and 60μm luminosities are calculated assuming H_0=75 kms-1Mpc^{-1}and q_0=0.5, and using the standard conversion from 60 and 100 μm flux (Helou et al. 1985). The final sample, together with FIR luminosities and basic data, is given in Table 1. The sample contains 45 radio–quiet quasars, of which 14 are in disturbed systems.

Assessing the morphology of the host galaxies of these quasars is critical to the present study and can be a difficult task. One may take one of two general approaches to the present data. We can choose to use homogeneous data, in this case the McLeod & Rieke H-band images, which may not be the best for the task but which will be fairly uniform in the information they provide on an individual object. Alternatively, one can take an inhomogeneous approach and use as much existing data as possible for any given object in the sample to arrive at what might be described as the best classification for that object given the data available. There are advantages and disadvantages to both approaches. In the homogeneous approach, it is clear that the McLeod & Rieke H-band images are not as well–suited to host galaxy studies as, say, deep HST images, since they are of limited angular resolution and depth. One is thus likely to be more subject to errors in morphological classification. In contrast, the inhomogeneous approach uses the best data available, including HST images for the sample discussed here. How-

ever, such data is not available for all objects, and so one might be subject to biases from the selection of PG quasars observed by HST.

Since each method has its own benefits and problems, we will use each in turn.

2.1 Homogeneous Image Classifications

The H-band observations of McLeod & Rieke provide us with a homogeneous imaging sample for the radio–quiet nearby PG quasars. To determine their morphologies the images were independently examined by three observers. They gave one of two classifications: class 0 for quiescent, undisturbed quasar hosts, and class 1 for disturbed hosts. In cases of disagreement the majority view is adopted. It would be nice to attempt a classification based on strength of merger. However, even with just two morphological classifications we are already running into problems with small number statistics. Therefore, for the present study, we must restrict ourselves to just the two classes 'disturbed' and 'quiescent'. Our classifications are shown in Table 2.

2.2 Inhomogenous Image Classifications

In Table 3 we summarise the results of host imaging studies of the objects in this sample from ten different literature sources. Most of these papers are concerned only with the imaging of host galaxies in general and are not biased towards studies aimed at FIR-luminous objects. One of the papers (Stockton et al. (1998)) is aimed at a specific object, PG1700+518, while only two, (Hutchings & Neff 1992), (Sanders et al. 1988b) *are* aimed at FIR luminous objects. These latter studies, though, only contribute corroborative classifications for other studies that are not biased in favour of FIR luminous objects. We thus hope to avoid biases introduced by having more data available for FIR luminous than for FIR faint objects.

For each object, a morphological class is provided by each study in which it is observed: class 0 for quiescent, undisturbed quasar hosts, and class 1 for disturbed hosts. A few objects have unclear classifications in some studies, and are given a ? designation. Most of these classes, excluding those based on the Mcleod & Rieke images, are provided by the authors of the collated papers. Classifications based on the McLeod and Rieke data are taken from Table 2.

A final morphological assessment is arrived at by comparing the results of all surveys that deal with a given object. Studies reaching fainter magnitudes and especially those working at higher spatial resolutions, using HST or adaptive optics, are given a higher weighting in deciding the final assessment.

A number of objects have seemingly contradictory morphological classifications in different studies. These are now discussed.

0052+251

Several bright objects near to the quasar might be thought to be interaction companions based on ground-based observations (eg. McLeod et al. (1994b), Dunlop et al. (1993), Hutchings et al. (1989)). However, HST images (Bahcall et al. 1997) reveal that the claimed second and third nuclei are in fact respectively an HII region in the host galaxy's spiral arms and a foreground star. The host appears to be an undisturbed spiral in the HST images. We therefore classify this object as quiescent.

0923+201

This object is a member of a small group of galaxies, and on this basis was thought to be interacting. HST data (Bahcall et al. (1997), McLure et al. (1998)) however show no signs of interaction, and the host galaxy appears to be a normal E2 elliptical. We thus classify this object as quiescent.

0953+414

The original H band images of McLeod & Rieke (1994b) show few signs of disturbance, consistent with initial HST observations by Bahcall et al. (1997). However, deeper optical (Hutchings et al. 1989) and IR (Dunlop et al. 1993) images from the ground suggested the presence of some disturbance. This has now been confirmed by deeper HST images (McLure et al. 1998) which reveal a tidal tail and up to four companions. We thus classify this object as disturbed.

1444+407

Optical images (Hutchings et al. 1989) suggested that this object might have an off-centre nucleus, indicating a disturbed morphology. However, ground-based infrared (McLeod & Rieke 1994b) and further optical (Hutchings & Neff 1992) observations have not confirmed this. HST images (Bahcall et al. 1997) show no signs of disturbance, but suggest the presence of a nuclear bar. We thus classify this object as quiescent.

1700+518

H band imaging of this object by McLeod & Rieke (1994b) shows no clear signs of disturbed structure. However, suggestions of disturbance were seen in ground-based optical data (Hutchings & Neff 1991). The situation has now been clarified by an adaptive optics study by Stockton et al. (1998) which has conclusively shown that this quasar is interacting with a nearby companion. Both companion and quasar host have tidal tails, and the redshift of the companion has been confirmed to be the same as the quasar. We must thus conclude that this is in fact an interacting system.

1211+143

The H band imaging from McLeod & Rieke (1994a) shows no signs of disturbance. However, deeper K band imaging by Dunlop et al. (1993) reveals a bridge linking the quasar to a companion galaxy. On this basis we classify this object as disturbed.

1229+204

This object appears undisturbed in the H band images from McLeod & Rieke (1994a). However, it is described as I? (possible interaction) by Hutchings et al. (1991). Since the evidence for an interaction is only marginal, we classify this object as quiescent.

1351+640

Optical observations have classified this object both as disturbed (Hutchings & Neff 1991) and quiescent (Hutchings & Neff 1992). The H band observations (McLeod & Rieke 1994a) suggest that this object has an offset nucleus and asymmetric inner isophotes. We thus tentatively classify this object as disturbed.

1612+261

This object was originally described as I?, a possible interaction (Hutchings et al. 1989). However, no signs of disturbance are visible in the H band images (McLeod &

Object	DLC	ACB	LD	Adopted
0026+129	0	0	1	0
0052+251	0	0	1	0
0157+001	1	1	1	1
0923+201	1	0	1	1
0947+396	1	1	1	1
0953+414	0	0	1	0
1012+008	1	1	1	1
1048+342	1	1	1	1
1121+422	0	0	0	0
1151+117	0	0	1	0
1202+281	1	1	1	1
1307+085	0	0	1	0
1309+355	0	1	0	0
1322+659	0	0	1	0
1352+183	0	0	0	0
1354+213	0	0	1	0
1402+261	0	0	0	0
1427+480	0	0	1	0
1444+407	0	0	0	0
1613+658	1	1	1	1
1700+518	0	0	0	0
0050+124	1	1	1	1
0804+761	0	0	0	0
0838+770	0	1	0	0
0844+349	1	1	1	1
1001+054	0	0	1	0
1114+445	0	1	0	0
1115+407	1	1	1	1
1211+143	0	1	0	0
1229+204	0	0	1	0
1351+640	1	0	0	0
1404+226	0	0	1	0
1411+442	0	0	1	0
1415+451	0	0	0	0
1416-129	0	0	1	0
1426+015	0	1	1	0
1435-067	0	0	1	0
1440+356	0	0	0	0
1519+226	0	0	0	0
1552+085	0	0	1	0
1612+261	0	0	1	0
1617+175	0	0	0	0
1626+554	0	0	0	0
2130+099	0	0	0	0
2214+139	0	1	0	0

Table 2. Homogeneous morphological classifications for PG quasars used in this study.

Objects classified as quiescent are indicated by 0, while 1 indicates classification as a disturbed object. Classifications were made independently by three experienced observers, including the author. The adopted morphology was then assigned the majority value in cases of disagreement.

Rieke 1994a). Since there is only marginal evidence for disturbance, we classify this object as quiescent.

2130+099

Ground–based optical imaging (Hutchings & Neff 1992), (Hutchings & Neff 1991) suggests that this object is interacting. H band images (McLeod & Rieke 1994a), however, reveal no signs of disturbance. In contrast to this, deeper K band imaging by Dunlop et al. (1993) show similar structures to the optical – bridges and companion objects – and reveal an additional companion not seen in the optical. We thus conclude that this object is disturbed.

3   COMPARISON OF DISTURBED AND UNDISTURBED QUASARS

Figure 1 compares the FIR luminosities of the disturbed and undisturbed quasars as a function of redshift for both the homogeneous and inhomogeneous classifications. There is a clear tendency for the disturbed quasars to have higher FIR luminosities. However, many of the objects in this sample only have IRAS upper limits. Detection rate statistics are thus also of interest. Of the 10 (15) quasars in disturbed hosts in the homogeneous (inhomogeneous) set, 6 (11) are detected at $60\mu m$ (i.e. 60% (73%)), whilst of the 35 (30) undisturbed host quasars, 17 (12) are detected (i.e. 48% (40%)). At 100 μm, 6 (9) of the 10 (15) disturbed host quasars are detected (60% (60%)) but only 8 (5) (22% (16%)) of the undisturbed host quasars. This is only indicative since the FIR flux limits for this sample are not uniform.

The large number of upper-limits in this dataset indicates that a full examination requires a Survival Analysis approach. These techniques allow the proper handling of 'censored' datasets – ie. those that contain many upper (or lower) limits. We apply a non-parametric univariate survival analysis test to detect differences in the FIR luminosities of the two classes of quasars. This test makes no assumptions about the underlying luminosity distributions of either sample i.e. it is non-parametric. We are thus not reliant on any particular models for the luminosity functions of these objects, which is useful since many aspects of quasar and ULIRG luminosity functions are still subject to debate. The method is, however, still dependent on the 'censoring' pattern, i.e. the manner in which upper limits are applied, in the compared samples. For example a bias might be introduced if the disturbed-host quasars were observed more deeply than the quiescent-host objects. However, no such bias is apparent in the data. We applied the Peto-Prentice statistical test to see if the two distributions are different using the ASURV Rev 1.2 package (LaValley et al. 1992), which implements the methods presented in Feigelson & Nelson (1985). This particular test was used since it is the least sensitive to differences in censoring patters.

We thus test whether the $60\mu m$ luminosity distributions of disturbed and undisturbed host quasars are different. $60\mu m$ luminosities were used because more of the quasars were detected at $60\mu m$ than $100\mu m$, minimising the effect of censoring patterns. We find that the probability that the difference in $60\mu m$ luminosity distributions between quasars with disturbed and undisturbed hosts could occur at random is 0.029 for the homogeneous dataset, and 0.0035 for the inhomogeneous. We thus have found a difference between the two with 97.1% confidence (99.65% confidence for the inhomogeneous set).

We also use the Kaplan-Meier estimator to derive values for the mean $60\mu m$ luminosity for each of the two classes of quasar. These were found to be $0.9 \pm 0.3 \times 10^{11} L_\odot$ for the quasars in undisturbed hosts and $3 \pm 1 \times 10^{11} L_\odot$ for the quasars in disturbed hosts ($0.5 \pm 0.1 \times 10^{11} L_\odot$ and $3 \pm 1 \times 10^{11} L_\odot$ respectively for the inhomogeneous dataset). While the small numbers of FIR luminous quasars in this sample implies that these values should be treated with caution, they nevertheless provide an interesting confirmation of the results of the Peto-Prentice test.

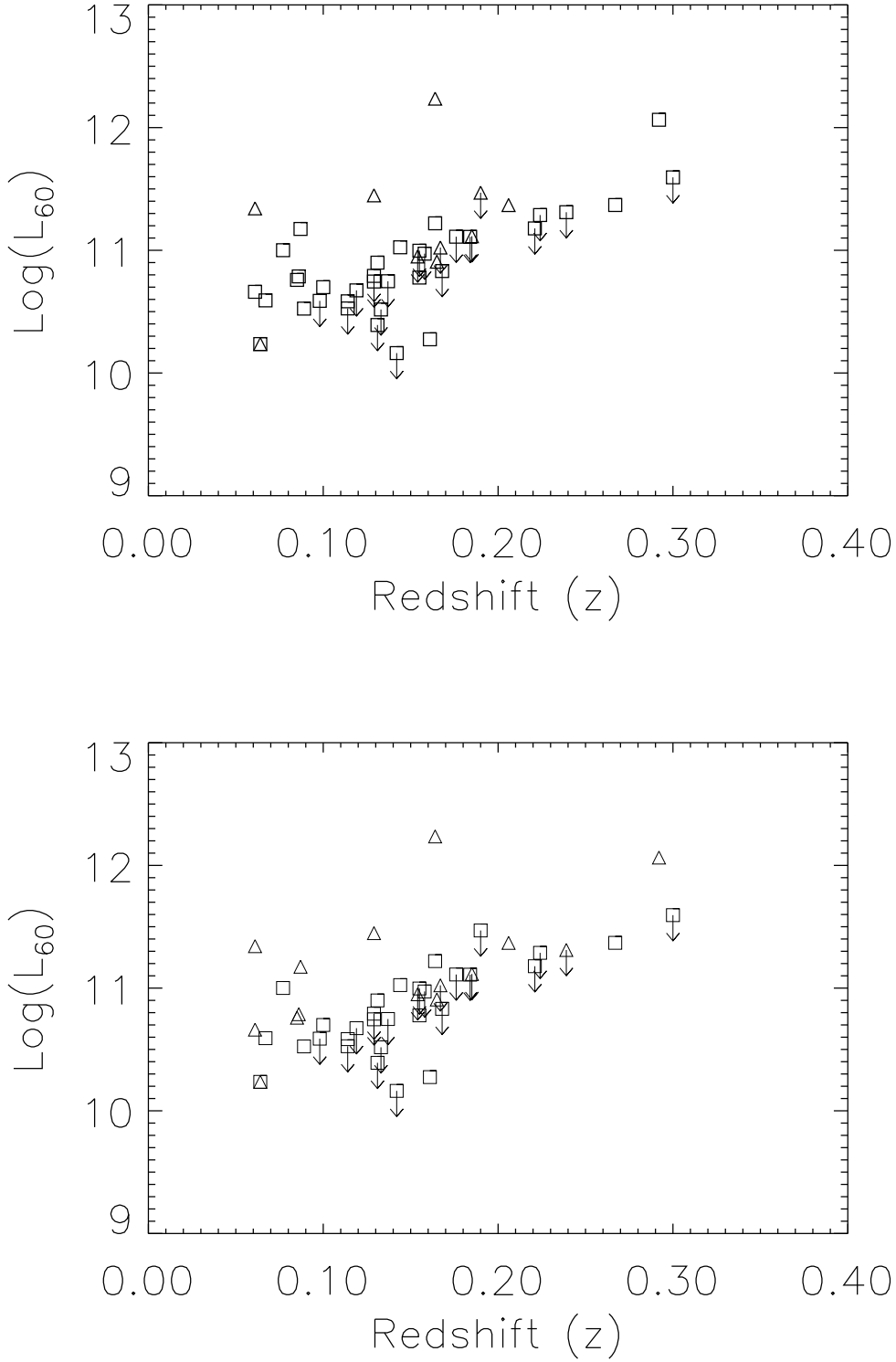We thus conclude that we have detected a significant

Figure 1. FIR Properties of Quasars in Disturbed and Undisturbed Hosts

(Upper) Homogeneous morphological classification; (Lower) Inhomogeneous morphological classification. Triangles are quasars in disturbed hosts, squares are quasars with undisturbed hosts. A line descending from the centre of the symbol indicates that the result is an upper limit. All upper limits are 3σ, all detections are at $> 3\sigma$.

Object	Paper										Adopted
	1	2	3	4	5	6	7	8	9	10	
0026+129		0									0
0052+251		0		1	0			1			0
0157+001		1		1			1		1	1	1
0923+201		1		0	0			1		0	0
0947+396		1									1
0953+414		0		1	?			1		1	1
1012+008		1		1	1			1		1	1
1048+342		1									1
1121+422		0									0
1151+117		0									0
1202+281		1			1						1
1307+085		0			0						0
1309+355		0			0						0
1322+659		0									0
1352+183		0									0
1354+213		0									0
1402+261		0			0						0
1427+480		0									0
1444+407		0			0	0		1			0
1613+658		1				1					1
1700+518		0	1				1				1
0050+124	1					1		1			1
0804+761	0										0
0838+770	0										0
0844+349	1					1					1
1001+054	0										0
1114+445	0										0
1115+407	1										1
1211+143	0			1							1
1229+204	0					?					0
1351+640	1					0	1				1
1404+226	0										0
1411+442	0										0
1415+451	0										0
1416-129	0										0
1426+015	0										0
1435-067	0										0
1440+356	0			0							0
1519+226	0										0
1552+085	0										0
1612+261	0								1		0
1617+175	0										0
1626+554	0										0
2130+099	0			1		1	1				1
2214+139	0					0					0

Table 3. Inhomogeneous morphological classifications for PG quasars used in this study.

Objects classified as quiescent in a given study are indicated by 0, while 1 indicates classification as a disturbed object. An unclear classification is indicated by ? for two objects. Papers referred to are: 1=(McLeod & Rieke 1994a); 2=(McLeod & Rieke 1994b); 3=(Stockton et al. 1998); 4=(Dunlop et al. 1993); 5=(Bahcall et al. 1997); 6=(Hutchings & Neff 1992); 7=(Hutchings & Neff 1991); 8=(Hutchings et al. 1989); 9=(Sanders et al. 1988b); 10=(McLure et al. 1998)

difference in 60μm luminosity between the two classes, with the disturbed-host quasars having luminosities 3–5 times greater than undisturbed-host quasars. This is apparent in both the homogenously classified dataset and is even more significant in the inhomogenously classified dataset. This argues strongly that the effect we are seeing is real, and that a full appraisal of the morphologies of these quasar hosts with, for example, HST, would only strengthen the result further.

3.1 FIR luminous galaxies containing quasars: A Coincidence?

Quasars and luminous FIR galaxies are both very rare classes of object. If their luminosity functions are independent, indicating that the quasar activity is unrelated to the FIR luminosity, then the joint luminosity function $\Phi(M_B, L_{FIR})$ will simply be

$$\Phi(M_B, L_{\mathrm{FIR}}) = \frac{\Phi_{\mathrm{QSO}}(M_B)\Phi_{\mathrm{IRAS}}(L_{\mathrm{FIR}})}{\Phi_{\mathrm{IRAS}}(L=0)}$$

For the absolute magnitude and FIR luminosity ranges of interest here, Φ_{QSO} and Φ_{ULIRG} are roughly the same at 10^{-6}–10^{-7} Mpc^{-3} (Krishna & Biermann 1998). Assuming that the luminosity functions are independent, we can then calculate the number of objects expected in the survey volume with both high FIR luminosity and a quasar in the absolute magnitude range of interest from $\Phi(M_B, L_{FIR})$ multiplied by the volume of the survey. This suggests we should expect $\sim 10^{-2}$—10^{-4} objects with $L_{FIR} > 10^{12}L_{\odot}$, when we actually find 4. This discrepancy, by a factor of at least 400, argues for a causal connection between the FIR luminosity, the disturbed morphology and the quasar activity. We discuss these issues in the next section.

4 DISCUSSION

4.1 Completeness and Bias

Whilst the PG quasar subsample we discuss above has complete imaging data from McLeod & Rieke (1994a,b), and plentiful additional data from other authors, it seems likely that it does not meet the ideal requirement that it be a complete sample of quasars. Recent results from a number of workers (e.g. Goldschmidt et al. (1992)) have suggested that significant incompleteness exists in the PG survey, especially at the low redshifts of interest to host morphology studies. We must thus be concerned that the undetermined causes of this incompleteness might undermine the basis for the present study. If absence of an object from the PG sample is correlated, for example, with high FIR luminosity or disturbed host morphology, then the results of the present study could be biased.

PG quasars were selected on the basis of UV excess, $U-B < -0.44$, and point like appearance in the optical. One prime candidate for the incompleteness is poor photometric accuracy (Goldschmidt et al. 1992). Photometric errors are random with respect to the nature of the objects since they will come from differences in the processing and analysis of each photographic plate on the sky. Incompleteness coming from photometric errors is thus unlikely to bias the present results.

Other effects, though, might be of greater concern. Examples include contamination of the quasar light by host galaxy emission, diluting the UV excess and dropping the quasar out of the PG selection; the presence of extended emission causing the object to be classified as a galaxy and not thus as a blue stellar object and candidate quasar; and finally, reddenning of the quasar light by dust in a host galaxy, again eliminating the UV excess.

If any of these effects favours the presence of FIR luminous quasars with disturbed hosts being in the PG Quasar catalogue, or removes FIR luminous quiescent host quasars, then the present result must be regarded as insecure. A definitive answer to this question, though, must wait until we have complete host imaging and FIR data for one of the new, complete, objectively selected surveys of nearby quasars such as the Hamburg survey (Köhler et al. 1997).

• **Colour Effects** The PG survey magnitudes were measured in a 5" aperture by an automatic plate scanner. A substantial amount of host galaxy light might thus be included, and thus the UV excess of the quasar might easily be diluted. McLeod & Rieke found that almost all of the host galaxies in their survey were spiral like. These will thus have $U-B$ colours between -0.2 and 0.5, with most objects being at the redder end. The host galaxies of the FIR luminous quasars are likely to have similar properties to ULIRGs. Arp 220, the archetypal ULIRG, has a $U-B = 0.33$. This is well within the range for normal spirals, so ULIRG-like objects will be affected in much the same way as objects with quiescent host galaxies. We thus do not expect colour dilution by the host galaxy to bias the present results.

• **Reddening** FIR luminous objects clearly contain a substantial mass of dust which might also lead to reddening of the emitted spectrum. This effect can clearly lead to the elimination of a UV excess and the loss of an object from the PG survey. This is perhaps the most worrying possible bias for the present work. One could easily imagine the presence of a population of reddened quasars that do not have UV excesses but that do have strong FIR luminosities. These objects would bias the present results if we make the unusual assumption that they are preferentially in undisturbed hosts. This idea can be observationally tested with the extensive flux limited redshift surveys of IRAS galaxies. If there were a large population of quiescent host, FIR luminous, reddened quasars, they would be found in surveys such as PSCz (Saunders et al., in preparation) or FSCz (Oliver et al. 1996). This does not seem to be the case (Oliver, private communication), since few unknown, FIR luminous quasars (i.e. high luminosity broad-line objects) appear in these surveys. It may well be that a population of completely obscured, FIR luminous quasars exists, analogous to Seyfert 2s and radio galaxies, but that is not relevant to the present study which deals only with optically identified broad-line objects. We thus conclude that reddening effects cannot significantly bias the present results.

• **Extended Emission** While many objects in the PG quasar catalogue do have extended nebulosities visible on the photographic plates (Schmidt & Green 1983), the survey was intended to select stellar images only. Thus objects which show very clear extended emission will be rejected. UV excess stellar sources were selected by eye from photographic plates. There are thus likely to be inconsistencies and inhomogeneities in the definition of a stellar object, but this is unlikely to be correlated with FIR properties. B band plate limits ranged from $B = 15.5$ to 16.67. Thus only fairly bright features would be seen. The elimination of extended sources in this way could remove quasars with bright host galaxies from the PG survey. The present result could be biased by this effect if quiescent host galaxies are preferentially excluded on the basis of their extended emission, and

some significant fraction of these had strong FIR emission. There are several counter arguments to this. An undisturbed quasar host galaxy will have the central engine lying at its own peak in surface brightness while a disturbed host quasar is more likely to have peaks in surface brightness offset from the central engine. A quasar in a disturbed host is thus more likely to be classified as extended than an undisturbed host. The absence of a significant number of previously unknown FIR-bright broad line objects in complete IRAS surveys, as discussed above, also argues against this idea. However, an alternative is that there is a population of disturbed-host quasars with *low* FIR luminosity that have been systematically overlooked as candidate PG objects. These could reduce the mean FIR luminosity of the disturbed-host class and reduce the significance of the result found in Section 3. For this to happen, the emission would have to appear above the plate limit and be sufficiently well–separated from the quasar nucleus for it to be seen as extended. This is clearly easier at lower redshifts, so we might expect there to be a deficit of lower redshift disturbed-host quasars in the PG survey. However, the disturbed host quasars appear over the whole of the limited redshift range in the present study, which argues against this possibility. This scenario, though, remains a possible alternative to the association of high FIR luminosity and disturbed quasar host morphology.

4.2   Far Infrared Emission in Quasar Hosts

We have found that there is a significant difference between the FIR luminosities of quasars in disturbed and undisturbed host galaxies. The mean luminosity of the disturbed-host quasars is several times greater than that of the quiescent-host quasars. These results argue that the FIR emission from quasars may have more to do with the host galaxy than with the central engine, and that it may have a similar origin to the strong FIR emission seen in ULIRGs. For many ULIRGs the dominant power source in the FIR seems to be a starburst (Genzel et al. 1998). Various authors have already used different lines of evidence to reach similar conclusions. Rowan-Robinson (1995) argues that the infrared emission of a sample of IRAS–detected PG quasars is coming from two components: hot dust in the narrow–line region dominating the $3–30\mu m$ emission, and a cooler, starburst powered component at $30–100\mu m$. This latter component would dominate the FIR luminosity that appears to be unusually strong in the disturbed–host quasars. Sopp & Alexander (1991), meanwhile, have used the results of radio observations to argue that there is a common origin for the radio and FIR emission in starbursts and radio-quiet quasars. This is based on the result that radio-quiet quasars lie on the same radio-FIR correlation as starbursts and other star-forming galaxies. In the light of these results and our own, it seems likely that the FIR emission from quasars may have more to tell us about the host galaxy than the central engine itself. The results from quasar surveys with ISO (eg. Wilkes et al. (1997)) should provide more information on this issue, and should be interpreted with host properties in mind. The situation is somewhat confused, however, by the recent results of Blundell et al. (1996, 1998) who argue, on the basis of small scale nuclear jets seen in radio quiet quasars with the VLBA, for a black-hole origin for the radio

emission. Quite how these objects would then appear on the same radio-FIR relation as starbursts is unclear.

4.3   The Nature of Quasar Evolution

We find that the numbers of FIR luminous quasars are substantially higher than would be expected if the quasar and high FIR luminosity were occurring independently. Together with the result that high FIR luminosity is associated with a disturbed host morphology, this looks suspiciously like the ULIRG-into-quasar scenario originally proposed by Sanders et al. (1988a). In this scheme quasars are triggered by galaxy mergers. The merger causes material in the interacting galaxies to fall towards the centre of the merged system. This appears to trigger a massive starburst, powering much, if not all, of the prodigious FIR luminosity seen in ULIRGs. Our new result might then confirm the earlier idea that some FIR-luminous galaxies also harbour quasars which are formed or re–awakened by the merger. As these systems evolve, the quasar gradually becomes visible, while signs of the merger decline, both in terms of enhanced FIR luminosity and disturbed host morphology. Quasars that lie in clearly disturbed systems would thus be at an earlier stage of evolution than the bulk of the population, and have stronger FIR luminosity.

However, it remains to be shown that the disturbed–host quasars are at an early stage of their development, since we have merely shown that their host galaxies show all the signs of a recent ULIRG-like interaction event. To do this one needs to examine the properties of the central engine itself as revealed, for example, by its emission and absorption line properties, or by its X-ray properties (Perry, private communication). If FIR luminous or disturbed–host quasars were found to deviate from the bulk of the quasar population in any central-engine properties, we would have not only a plausible reason to suggest that they were at a different stage in their evolution, but also an indication of the physics of that evolution. In this context it is interesting to note work by Lipari (1994) on extreme FeII emitting AGN, many of which are FIR luminous.

If mergers do indeed trigger quasar activity, via a ULIRG stage, then we may have an interesting new perspective on the so–called quasar epoch at z=2–3 (see eg. Dunlop & Peacock (1990) and Shaver et al. (1996)). Current galaxy formation theories suggest that galaxies formed by the merging of smaller sub-units (eg. Kauffman (1995)). Observations of the Hubble Deep Field (eg. Clements & Couch (1996b), Abraham et al. (1996)) show that many high redshift, candidate primeval galaxies are indeed very disturbed, possibly merging, systems. If high redshift mergers trigger ULIRG-like activity, as they appear to in the nearby universe, and ULIRGs lead in some cases to quasars, then we could speculate that the epoch of rapid galaxy sub-unit merging might also be the epoch of strongest quasar activity. The z=2–3 quasar–epoch might thus be indicating the time when most galaxies underwent their major merging phase.

4.4   Confirmation of this result

While this result seems fairly secure, for the reasons expounded above, the current state of knowledge of quasar

hosts and FIR emission is not so good that we can be absolutely sure of our conclusions. Before we can say that, a number of caveats must be investigated.

Firstly, we must improve our knowledge of the local quasar host population. For the present study we have either had to use limited IR morphological data, or had to bring together results from disparate studies at a range of wavelengths and with differing depths and angular resolutions. This is not an ideal situation. Far better would be a consistent survey of all the low redshift PG quasars dealt with in this paper reaching faint fluxes (eg. reaching surface brightness levels of R=26 mag arcsec^{-1} as in McLure et al. (1998)) with good angular resolution (0.5 arcsec or better). This might be achieved with a large HST survey, though it is interesting to note that only ten of the 45 PG quasars discussed here have been observed since its launch. Alternatively, large ground-based telescopes equipped with adaptive optics might achieve this goal.

Secondly, we must be sure that there is no significant population of disturbed-host non-FIR luminous quasars which, as discussed above, might have been missed by the PG quasar survey, and produce biases in the present study. This could be achieved by mounting a host galaxy imaging survey of recent objectively selected quasar surveys eg. the Hamburg survey (Köhler et al. 1997) with similar parameters as the study suggested above for PG quasars.

Finally, our knowledge of the FIR emission of quasars must also be improved. Some steps towards this have been made by ISO (Wilkes et al. 1997), but these samples are still quite small and will not have reached the necessary sensitivity in many cases. Instead we must look to SIRTF and SOFIA as our best hopes for obtaining the necessary FIR observations at high enough sensitivities. The new generation of submillimetre bolometer arrays (eg. SCUBA) might also have a role to play by providing submillimetre rather than FIR fluxes.

5 CONCLUSIONS

We have compared the FIR properties of quasars with disturbed and undisturbed host galaxies in a redshift and absolute optical magnitude limited subsample of the PG quasar survey. We find that those objects with disturbed hosts have a significant tendency to having greater FIR luminosities. We also find that FIR luminous quasars occur in greater numbers than would be expected if the quasar and high FIR luminosities were independent. This result is consistent with the view that ULIRGs and quasars are related phenomena. However, there are several reasons why these results might be incomplete or biased, including the morphological classifications which are based on an inhomogeneous set of observations, and the use of the PG survey itself, which may be biased and incomplete. Specifically, if the PG survey is biased away from selecting non-FIR luminous quasars with interacting hosts, the present results would have to be revised. Improved quasar host morphologies, from homogeneous deep high resolution surveys, and better FIR data would allow us to place the present result on a firmer footing. Such morphological studies are possible with HST, or ground–based adaptive optics systems, while improved FIR data will have to await SIRTF or SOFIA.

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